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Quantifying differences in land use emission estimates implied by definition discrepancies

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Abstract. The quantification of CO_2 emissions from anthropogenic land use and land use change (eLUC) is essential to understand the drivers of the atmospheric CO_2 increase and to inform climate change mitigation policy. Reported values in synthesis reports are commonly derived from different approaches (observation-driven bookkeeping and process-modelling) but recent work has emphasized that inconsistencies between methods may imply substantial differences in eLUC estimates. However, a consistent quantification is lacking and no concise modelling protocol for the separation of primary and secondary components of eLUC has been established. Here, we review differences of eLUC quantification methods and apply an Earth System Model (ESM) of Intermediate Complexity to quantify them. We find that the magnitude of effects due to merely conceptual differences between ESM and offline vegetation model-based quantifications is $\sim 20\,\%$ for today. Under a future business-as-usual scenario, differences tend to increase further due to slowing land conversion rates and an increasing impact of altered environmental conditions on land-atmosphere fluxes. We establish how coupled Earth System Models may be applied to separate secondary component fluxes of eLUC arising from the replacement of potential C sinks/sources and the land use feedback and show that secondary fluxes derived from offline vegetation models are conceptually and quantitatively not identical to either, nor their sum. Therefore, we argue that synthesis studies should resort to the "least common denominator" of different methods, following the bookkeeping approach where only primary land use emissions are quantified under the assumption of constant environmental boundary conditions.

1 Introduction

Anthropogenic emissions of CO_2 are the main driver for observed climate change (Stocker et al., 2013b) and primarily result from the combustion of fossil fuels and anthropogenic land use and land use change (LUC) (Le Quéré et al., 2015). Conceptually, fossil fuel emissions can be regarded as an external forcing acting upon the C cycle-climate system. In contrast, LUC additionally modifies the response of terrestrial ecosystems to elevated CO_2 and changes in climate (Gitz and Ciais, 2003; Strassmann et al., 2008) and thereby affects the C cycle-climate feedback (Joos et al., 2001; Friedlingstein et al., 2006; Stocker et al., 2013a). This leaves room for interpretations as to how exactly land use change emissions (eLUC) are to be defined and where the system boundaries are to be drawn.

The definition of eLUC is relevant for the accounting of the global C budget (Ciais et al., 2013). Top-down derived land-atmosphere C fluxes that are not explained by bottom-up estimates of eLUC are commonly ascribed to the *residual terrestrial C sink*. Differences in the definition of eLUC thus directly translate into differences in estimates for the residual terrestrial C sink. This budget term is a major source of uncertainty in climate projections (Jones et al., 2013) and its quantitative understanding motivates a large part of current research in biogeochemistry and terrestrial ecology.

Common to almost all approaches to quantify "CO_2 emissions from land use change" using global process-based models, is that eLUC is calculated as the difference in the global total land-to-atmosphere flux (F) between a realistic world where land vegetation cover and C pools are affected by prescribed, time-varying LUC maps (subscript LUC) and a hypothetical world, where no LUC is occurring (subscript 0):

$$eLUC = F_{LUC} - F_0. \quad (1)$$

However, the definition or model setup, under which F_{LUC} and F_0 are calculated, is relevant as it implies the inclusion of secondary fluxes. Strassmann et al. (2008) (henceforth termed SM08) laid out a framework to distinguish between different component fluxes arising from land use, including primary emissions from converted land, and secondary emissions arising from the interactions between climate, CO_2 and LUC. Pongratz et al. (2014) (henceforth termed PG14) show that numerous different definitions of eLUC have been used in the published literature, implying a bewildering array of different combinations of component fluxes that are counted towards eLUC in the different studies. SM08 and PG14 demonstrate conceptually that due to this, typical eLUC estimates derived from observation-driven bookkeeping models, offline Dynamic Global Vegetation Models, and coupled Earth System Models give systematically different results.

Substantial, setup-related differences in eLUC estimates have been found in earlier studies (Strassmann et al., 2008; Arora and Boer, 2010; Gasser and Ciais, 2013), and different component fluxes have been identified and quantitatively separated within their respective modelling framework (Gitz and Ciais, 2003; Strassmann et al., 2008). SM08 distinguished between primary emissions that capture the direct effects of land conversion, and secondary effects arising from the interaction of land conversion and environmental change (CO_2 and climate). SM08 further separated the secondary fluxes into the *land use feedback flux* and the *replaced sinks/sources flux*. We term these eLFB and eRSS, respectively, and provide definitions in Sect. 3 and quantifications in Sect. 5. Recently, Gasser and Ciais (2013) (GC13) provided quantitative estimates of historical eLUC following different definitions. However, their analysis is limited to offline vegetation model quantifications and thus cannot address the aforementioned discrepancies between offline and ESM methods.

Here, we apply a single model, use a simple formalistic description of eLUC flux components inspired by GC13 and SM08, and follow the classification of PG14 to distinguish different methods of eLUC quantification. We quantify these differences for the historical period and a future business-as-usual scenario (RCP8.5). In contrast to earlier studies (Strassmann et al., 2008; Arora and Boer, 2010), we designed model setups to limit differences in eLUC to merely conceptual ones by using climate and CO_2 outputs from the coupled simulations to drive offline simulations, instead of using observational data for the latter. We will demonstrate that such definition differences imply inconsistencies of estimated land use emissions on the order of 20 % on the global scale and may increase to 30 % under a future business-as-usual scenario. This is directly relevant for territorial C balance accounting and national greenhouse gas balances under the Kyoto Protocol and thus inherently carries a political relevance.

We elucidate the implications of the choice of definition for the residual terrestrial C sink and global C budget accounting and discuss how eLUC quantifications may most appropriately be defined in studies that rely on multiple methodological approaches. In such cases, we propose, following Houghton (2013), to resort to the "least common denominator", following the bookkeeping approach (method D1 in PG14), where LUC emissions are defined without accounting for any indirect effects on terrestrial C storage caused by transient changes in CO_2 or climate.

2 Brief overview of methods D1, D3, and E2

We start by revisiting the classification of PG14 for a subset of eLUC quantification methods identified in their study. We focus our analysis on the discrepancy between eLUC derived from bookkeeping and offline vegetation models (D1 and D3 methods) and coupled ESMs (E2 method). Results of the D3 method feature prominently in model intercomparison studies (McGuire et al., 2001; Sitch et al., 2008), the Global Carbon Project (Le Quéré et al., 2015) and the IPCC (Ciais et al., 2013), and are often presented along with and compared against D1-type estimates. Yet, a consistent separation of commonly identified component fluxes can only be achieved by ESMs (see below).

2.1 Bookkeeping method (D1)

The first global quantifications of CO_2 emissions from LUC were based on bookkeeping models that track the fate of C after conversion from natural to cropland or pasture vegetation or vice versa (Houghton et al., 1983). Updated bookkeeping estimates of eLUC (Houghton, 1999; Houghton et al., 2012) still represent the benchmark against which process-based models with prognostic vegetation C density are often compared (Le Quéré et al., 2015). Bookkeeping models use observational information of C density in natural and agricultural vegetation and in different biomes to calculate eLUC (Houghton et al., 1983). Environmental boundary conditions thus implicitly represent fixed conditions under which the observations are taken, i.e. climate, CO_2, and N-deposition levels of recent decades. Process-based vegetation models can be run in a conceptually corresponding setup ("bookkeeping method" in SM08 and thereafter) by holding environmental boundary conditions constant. While bookkeeping models are designed to derive LUC-related C emissions from a single simulation (method termed B in PG14), process-based models commonly take the difference in the net land-to-atmosphere carbon flux (F) between a simulation with and one without LUC (method D1; see Eq. 2). Here, these conceptually comparable methods are both referred to as bookkeeping method. For method D1 it holds

$$e\mathrm{LUC}_{\mathrm{D1}} = F^{0}_{\mathrm{LUC}} - F^{0}_{0}. \quad (2)$$

In general, F refers to a global annual flux, but equations provided here are valid also for cumulative fluxes and smaller spatial domains. Constant environmental boundary conditions (CO_2, climate, nitrogen deposition etc.) in both simulations are reflected by superscript "0". F^0_0 is the land-atmosphere flux in the reference state, which may either be forced with the land use distribution at the beginning of the transient simulation (year 1700 here, see Sect. 4) or zero anthropogenic land use. This choice affects secondary fluxes. Models are commonly spun up to equilibrate C pools and hence F^0_0 is zero except for net land-atmosphere CO_2 fluxes occurring due to unforced climate variability.

Internal, unforced climate variability may affect the quantification of eLUC as climate variability affects the land-atmosphere carbon flux F. Ideally, the model setup should be such that internal, unforced variability evolves identically in both simulations. Then the land-atmosphere fluxes from land not affected by LUC and caused by internal variability would cancel when evaluating Eq. (2). In practice, this may be difficult to achieve for some state-of-the-art Earth System Models as LUC affects heat and water fluxes and thus climate. A potential solution is to run the land module offline in both simulations or to force the land module in the simulation with LUC by using climate output from the reference simulation without LUC.

eLUCdI is equivalent to primary emissions (see Sect. 3) and captures instantaneous CO_2 emissions occurring during deforestation and C uptake during regrowth, as well as delayed (legacy) emissions from wood product decay and the gradual re-adjustment of soil and litter C stocks to altered input levels and turnover times. Depending on the model, eLUCdI may also include effects of shifting cultivation (cycle of cutting forest for agriculture, then abandoning) and wood harvest. eLUCdI is determined by the spatio-temporal information of land use change, C inventories in natural and agricultural land and the response timescales of C pools after conversion.

2.2 Climate and CO_2-driven offline models (D3 method)

Prognostically simulating vegetation C density instead of prescribing it has the advantage that secondary effects under environmental change can be simulated. The first such study using a set of process-based vegetation models with prescribed, transiently varying climate and CO_2 from observed historical data was presented by McGuire et al. (2001). This method is termed D3 following the classification of PG14 and is also referred to as an "offline" setup, commonly applied to stand-alone Dynamic Global Vegetation Models (DGVM) or Terrestrial Ecosystem Models (TEM).

$$e\mathrm{LUC}_{\mathrm{D3}} = F^{\mathrm{FF+LUC}}_{\mathrm{LUC}} - F^{\mathrm{FF+LUC}}_{0} \quad (3)$$

Here, the superscripts indicate that actually observed, time-varying environmental conditions (climate, CO_2, N-deposition, etc.) are the result of fossil fuel emissions and other non-LUC related forcings (FF), and land use change (LUC), and are prescribed in the LUC and in the non-LUC simulation. This also corresponds to the setup used in GC13 for quantifying "emissions from land use change". Their "CCN" perturbation is analogous to what the superscript "FF + LUC" represents.

2.3 Emission-driven coupled Earth System Models (E2)

For a consistent separation of total CO_2 emissions related to LUC, emission-driven, coupled Earth System Models (ESM) may be applied. In such a setup, climate and atmospheric CO_2 interactively evolve in response to anthropogenic land use change, fossil fuel emissions, and other forcings. This method is termed E2 following the classification of PG14 and is typically computed with ESM or simpler atmosphere–ocean–land climate-carbon models:

$$e\mathrm{LUC}_{\mathrm{E2}} = F^{\mathrm{FF+LUC}}_{\mathrm{LUC}} - F^{\mathrm{FF}}_{0}. \quad (4)$$

Here, the superscript "FF" corresponds to the environmental conditions simulated with prescribed fossil emissions and other non-LUC related anthropogenic or natural forcing, whereas superscript "FF + LUC" refers to a simulation where environmental conditions evolve interactively in response to LUC-related emissions, as well as the "FF" forcing. As noted also in earlier publications (Strassmann et al., 2008; Arora and Boer, 2010; Pongratz et al., 2014), here, in contrast to the D3 method, environmental conditions in the LUC and non-LUC simulation differ. In the non-LUC case, climate and CO_2 are consistent with absent LUC, and hence CO_2 is lower in the non-LUC simulation. This implies a systematic difference in flux quantifications following the D3 and E2 methods. This difference may be expressed as flux components that are either ascribed to total eLUC or not. Below, we will identify a set of commonly defined flux components and investigate the discrepancies between methods D1, D3, and E2 conceptually (Sect. 3) and quantitatively (Sect. 5).

Unforced climate variability will evolve differently in the two ESM simulations as the applied forcing is different. The component in $F^{\mathrm{FF+LUC}}_{\mathrm{LUC}}$ and F^{FF}_{0} arising from differences in internal variability will be attributed to eLUCeII according to Eq. (4). This misattribution could be significant in particular when considering small regions and short timescales. Ensemble simulations would be required to quantify the impact of internal climate variability on eLUCeII. Alternatively, averaging over a large spatial domain and temporal smoothing tends to moderate the influence of unforced variability on eLUCeII.

3 Defining flux components

SM08, PG14, and GC13 establish a formalism to describe and discuss the different definitions of total eLUC and its component fluxes. Here, we synthesize these previous frameworks to a minimal description that allows us to identify the different flux components contained in eLUC provided by the offline DGVM setups (D3 method), coupled ESM model setups (E2 method), and the bookkeeping approach (D1 method). We then show that $e\mathrm{LUC}_{\mathrm{E2}} = e\mathrm{LUC}_0 + e\mathrm{RSS} + e\mathrm{LFB}$ plus synergy terms. We propose a definition for the delineation between component fluxes that follows a separation along underlying drivers of environmental changes, and that allows a consistent identification of component fluxes in coupled model setups with and without the FF forcing. The formalism presented below sets the basis for the analysis and discussion in subsequent sections.

A reference time (or period) t_0 is selected. At t_0 all land with total area A_0 is "undisturbed" with respect to land use changes that take place *after* t_0. The reference area A_0 may include agricultural land that was converted before t_0. Net atmosphere-land carbon fluxes at t_0 and thereafter may not vanish as the land system may not be in equilibrium with the atmosphere. Under commonly used model setups, the extent of agricultural land in the reference state is small in comparison to the area under natural vegetation. Similarly, models are typically spun-up towards equilibrium and remaining trends in atmosphere-land fluxes are small. For simplicity, we neglect these disequilibrium fluxes below.

Additional fluxes arise due to forcings that occur after the reference time. We separate forcings into a land use change (LUC) and a non-land use change component (FF) such as fossil fuel emissions, nitrogen deposition, ozone changes etc. In a simulation without LUC, these additional fluxes occur on undisturbed land (subscript "und") and are caused by FF (use of superscript analogous as in Eqs. 3 and 4) and we write $F_0^{\mathrm{FF}}(t) = A_0\,\Delta f_{\mathrm{und}}^{\mathrm{FF}}(t)$. Δ denotes a change in a variable relative to the reference time t_0 (e.g. $\Delta f(t) = f(t) - f(t_0)$). Note that $f^{\mathrm{FF}}(t_0)$ is zero by definition. Below, we drop the specification of t. In a simulation with LUC, we can write fluxes occurring over land that has not been converted since the reference time t_0 (subscript "und") and land that has been converted after t_0 (subscript "dis") as

$$F_{\mathrm{LUC}}^{\mathrm{FF+LUC}} = \underbrace{(A_0 - \Delta A)\,\Delta f_{\mathrm{und}}^{\mathrm{FF+LUC}}}_{\text{undisturbed land}} + \underbrace{\Delta A\left(f^0 + \Delta f_{\mathrm{dis}}^{\mathrm{FF+LUC}}\right)}_{\text{disturbed land}}. \quad (5)$$

ΔA is the total area that has been converted, e.g. from natural to cropland or vice versa, since the reference time and up to the point in time of interest. Note that disturbed and undisturbed land both "see" the environmental forcing caused by FF *and* LUC. GC13 treat fluxes on disturbed land as a vector representing land area cohorts that have transitioned from natural to agricultural land at a given time. Here, we drop the vector notation for individual age cohorts after conversion and lump these into a scalar representing non-natural (agricultural) land of varying age ($\Delta A\,(f^0 + \Delta f_{\mathrm{dis}}^{\mathrm{FF+LUC}})$). f^0 are direct emissions in response to land conversion under constant environmental conditions and comprise instantaneous and legacy fluxes due to LUC after t_0 as identified by I_u and L_u in PG14; $\Delta f_{\mathrm{dis}}^{\mathrm{FF+LUC}}$ is its modification due to environmental change (δI and δL in PG14). Note that on long timescales, the cumulative flux of ($\Delta f_{\mathrm{dis}}^{\mathrm{FF+LUC}}$) is independent of the magnitude of f^0.

Using Eq. (4) and $\Delta f^{\mathrm{FF+LUC}} = \Delta f^{\mathrm{FF}} + \Delta f^{\mathrm{LUC}} + \delta$ allows us to expand and re-arrange terms in Eq. (5) and to write the total C flux induced by LUC after t_0 as a sum of commonly separated component flux components, primary emissions (eLUCo), replaced sinks/sources (eRSS), and the land use feedback flux (eLFB) plus synergy terms:

$$e\mathrm{LUC}_{\mathrm{E2}} = F_{\mathrm{LUC}}^{\mathrm{FF+LUC}} - F_0^{\mathrm{FF}} \quad (6)$$

$$= \Delta A\left(\Delta f_{\mathrm{dis}}^{\mathrm{FF}} - \Delta f_{\mathrm{und}}^{\mathrm{FF}}\right) \quad (e\mathrm{RSS}) \quad (7)$$

$$+ (A_0 - \Delta A)\,\Delta f_{\mathrm{und}}^{\mathrm{LUC}} + \Delta A\,\Delta f_{\mathrm{dis}}^{\mathrm{LUC}} \quad (e\mathrm{LFB}) \quad (8)$$

$$+ \Delta A\, f^0 \quad (e\mathrm{LUC}_0) \quad (9)$$

$$+ (A_0 - \Delta A)\,\delta_{\mathrm{und}} + \Delta A\,\delta_{\mathrm{dis}} \quad (\text{synergy}). \quad (10)$$

We emphasize that eLUC includes only those fluxes due to land conversion after the reference time. Any legacy fluxes from land conversion before t_0 are not included. Atmosphere-land fluxes arising from a disequilibrium at t_0 affect $F_{\mathrm{LUC}}^{\mathrm{FF+LUC}}$ and F_0^{FF} and thus cancel, apart from synergy terms. $A_0\,\Delta f_{\mathrm{und}}^{\mathrm{FF}}$ is the land-atmosphere flux in a simulation forced only by FF and can be interpreted as the potential land C sink (ePS) under environmental change caused by FF.

$$e\mathrm{PS} = A_0 \Delta f_{\mathrm{und}}^{\mathrm{FF}}. \quad (11)$$

The above definition (Eqs. 6–10) of the total C flux induced by LUC corresponds to the E2 method, $e\mathrm{LUC}_{\mathrm{E2}}$ (Eq. 4). $e\mathrm{LUC}_0$ are primary emissions and equivalent to $e\mathrm{LUC}_{\mathrm{D1}}$, as quantified using a bookkeeping approach. Analogously, component fluxes of the land-atmosphere CO_2 exchange in the different model setups F_i^k can now be identified (see Table 2).

In spite of the variety of terminologies presented in the published literature, studies generally agree that total C fluxes induced by LUC can be split into primary emissions, eLUCo, that capture the direct effects of land conversion, and secondary effects arising from the interaction of land conversion and environmental change (CO_2, climate). However, the exact delineation between secondary emissions eLFB and eRSS differs (Strassmann et al., 2008; Pongratz et al., 2009, 2014). Here, we chose a definition so that eRSS arises due to environmental changes (e.g. CO_2, climate, N-deposition, ozone, air pollution, etc.) that are not caused by LUC, whereas eLFB is due to environmental changes driven by LUC. According to Eq. (8) and for a reference state without land under use, eRSS can be interpreted as the difference in sources/sinks between land under potential natural vegetation ($\Delta f_{\mathrm{und}}^{\mathrm{FF}}$) and agricultural land ($\Delta f_{\mathrm{dis}}^{\mathrm{FF}}$) and scales with the area of land converted ΔA. The LUC-feedback flux eLFB (Eq. 9) describes the flux arising as a consequence of LUC-induced environmental changes (e.g. CO_2, climate change). eLFB occurs on non-converted (natural) and converted (agricultural) land, with different sink strength ($\Delta f_{\mathrm{und}}^{\mathrm{LUC}}$ and $\Delta f_{\mathrm{dis}}^{\mathrm{LUC}}$). To sum up, eRSS arises from secondary effects of fossil fuel emissions (and N deposition, etc.), whereas eLFB is driven only by LUC. This is reflected by the fact that only superscript "LUC" occurs in the definition of eLFB, whereas only "FF" occurs in the definition of eRSS. The definitions of eRSS, and hence of eLFB differ slightly between publications (Strassmann et al., 2008; Pongratz et al., 2014). SM08 defined eLFB so that this flux only occurs on remaining natural land. Specifically, the term ($\Delta A\, \Delta f_{\mathrm{dis}}^{\mathrm{LUC}}$) appears in eLFB here, while it is ascribed to eRSS in SM08. However, this flux component is relatively small (see Fig. 1). As indicated by PG14, eRSS may also be defined as $e\mathrm{RSS} = \Delta A(\Delta f_{\mathrm{dis}}^{\mathrm{FF+LUC}} - \Delta f_{\mathrm{und}}^{\mathrm{FF+LUC}})$, implying that $e\mathrm{LFB} = A_0\, \Delta f_{\mathrm{und}}^{\mathrm{LUC}}$. Our choice of eRSS and eLFB has the advantage that it follows an intuitive separation between underlying environmental drivers (FF vs. LUC) and that eLFB can identically be separated in coupled ESM-type simulations where the FF forcings are excluded. This corresponds to the E1 definition in PG14, with $e\mathrm{LUC}_{\mathrm{E1}} = F_{\mathrm{LUC}}^{\mathrm{LUC}} - F_0^0 = e\mathrm{LUC}_0 + e\mathrm{LFB}$, and was applied by Pongratz et al. (2009) and Stocker et al. (2011).

For clarity, we have dropped the temporal and spatial dimensions of fluxes and areas and have reduced the formalism to a distinction only between undisturbed and disturbed (converted) after the reference time t_0. This is a simplification for a formal illustration and we note that the simulations presented in Sect. 5 account for the full complexity of fluxes across space, different agricultural and natural vegetation types, and time.

As pointed out in earlier publications by SM08, PG14, and Arora and Boer (2010), as well as in Sect. 1, eLUCdIII and eLUCeII are not identical and hence eLUCdIII cannot be written as the sum of component fluxes identified above. In other words, while primary emissions eLUCo can be consistently derived from offline DGVMs by simply holding environmental conditions constant, the secondary fluxes derived from such studies are neither equal to eRSS, nor eLFB, nor the sum of the two. In other words, eRSS and eLFB cannot be separated as shown here using offline vegetation models.

$$e\mathrm{LUC}_{\mathrm{D3}} - e\mathrm{LUC}_0 \neq e\mathrm{RSS} + e\mathrm{LFB}. \quad (12)$$

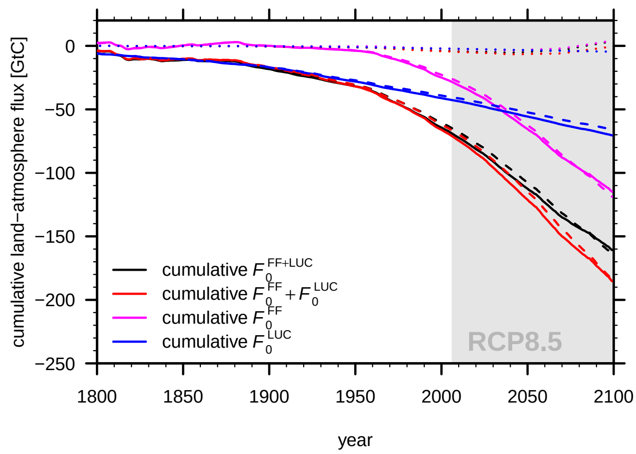

Figure 1. Global cumulative net land-to-atmosphere CO_2 fluxes induced by environmental change caused by FF (F_0^{FF}), LUC (F_0^{LUC}), their combined effect ($F_0^{\mathrm{FF+LUC}}$), and the sum of individual effects ($F_0^{\mathrm{FF}} + F_0^{\mathrm{LUC}}$). Curves represent cumulative global fluxes induced by environmental change, weighted by their time-varying area of natural vegetation (dashed lines), croplands and pastures land (dotted lines), and their sum (solid lines). Note that this excludes all direct effects of LUC. The differences between the combined and the sum of effects correspond to the synergy terms δ, following Stein and Alpert (1993). The model setups are described in Tables 1 and 2.

By expanding terms analogously to above derivation, the difference between eLUC quantifications from the E2 and the D3 methods turns out to be

$$e\mathrm{LUC}_{\mathrm{E2}} - e\mathrm{LUC}_{\mathrm{D3}} = A_0 \left(\Delta f_{\mathrm{und}}^{\mathrm{LUC}} + \delta_{\mathrm{und}} \right). \quad (13)$$

Ignoring the synergy term δ_{und}, the discrepancy can thus be interpreted as a flux, triggered by environmental changes caused by LUC, but occurring on land not converted since the reference period ($\Delta f_{\mathrm{und}}^{\mathrm{LUC}}$). Note that this is not identical to eLFB as defined here. The same theoretical result can be found when applying the formalism of PG14 and their definition of flux components in eLUCeII and eLUCdIII, with the difference turning out to be $(\delta_l + \sigma_{l,f})(E_n + E_p)$.

In the literature, eLUC estimates from bookkeeping (corresponding to D1) and offline vegetation models following the D3 method are often presented alongside (Ciais et al., 2013; Le Quéré et al., 2015). Conceptually, they are not identical and estimates thus imply systematic differences. We can analogously decompose the fluxes in each simulation (see also Table 2) and write this difference as

$$e\mathrm{LUC}_{\mathrm{D3}} - e\mathrm{LUC}_{\mathrm{D1}} = e\mathrm{RSS} + \Delta A \left(\Delta f_{\mathrm{dis}}^{\mathrm{LUC}} - \Delta f_{\mathrm{und}}^{\mathrm{LUC}} \right) + \Delta A \left(\delta_{\mathrm{dis}} - \delta_{\mathrm{und}} \right). \quad (14)$$

Note that the term $\Delta A(\Delta f_{\mathrm{dis}}^{\mathrm{LUC}} - \Delta f_{\mathrm{und}}^{\mathrm{LUC}})$ is sometimes included in eRSS implying that the difference between D3 and D1 is described simply by eRSS. However, our definition of eRSS differs.

Table 1. Model setups. F is the simulated total net flux of C from the terrestrial biosphere to the atmosphere. Subscript 0 refers to a setup where the area under use is kept constant at 1700 conditions and subscript LUC to a setup where the area under use is transiently varying following the land cover data by Hurtt et al. (2006). Superscript LUC and FF refer to environmental changes (CO_2, climate, etc.) due to LUC forcing and non-LUC related forcing (FF) or their combination (FF + LUC). Simulations with superscript "0" are forced by constant environmental (climate and CO_2) conditions (e.g. preindustrial or modern). In coupled simulations, climate and CO_2 evolve interactively as simulated by the coupled Bern3D-LPX model. The offline model mode uses either outputs from the coupled simulations or constant climate and CO_2 and F is computed with the stand-alone vegetation model LPX. N-deposition ("N-dep.") is prescribed from Lamarque et al. (2011).

Setup	model mode	Climate	CO_2	LUC	FF	N-dep.
$F_{\text{LUC}}^{\text{FF+LUC}}$	coupled	interactive	interactive	on	on	on
$F_{\text{LUC}}^{\text{LUC}}$	coupled	interactive	interactive	on	off	const.
F_{0}^{FF}	coupled	interactive	interactive	const.	on	on
F_{0}^{LUC}	offline	from $F_{\text{LUC}}^{\text{LUC}}$	from $F_{\text{LUC}}^{\text{LUC}}$	const.	–	const.
$F_{0}^{\text{FF+LUC}}$	offline	from $F_{\text{LUC}}^{\text{FF+LUC}}$	from $F_{\text{LUC}}^{\text{FF+LUC}}$	const.	–	on
F_{LUC}^{0}	offline	constant	constant	on	–	const.
F_{0}^{0}	offline	constant	constant	const.	–	const.

4 Methods

In order to quantify the individual flux components and the discrepancy between the different quantifications of eLUC outlined in previous sections, we apply the emission-driven, coupled Bern3D-LPX Earth System Model of Intermediate Complexity as described in Stocker et al. (2013a) and the offline DGVM model setup where the LPX DGVM is driven in an offline mode as described in Stocker et al. (2014). Results from the offline vegetation model were also used in global C budget accountings (Le Quéré et al., 2013; Le Quéré et al., 2014, 2015), following the D3 method for estimating eLUC therein. The model is spun up at constant boundary conditions representing year 1700 (CO_2 insolation, HYDE-based, (Goldewijk, 2001) land use distribution from the LUH data set (Hurtt et al., 2006), and recycled 1901–1931 CRU TS 2.1 climate (Mitchell and Jones, 2005)). Model drift is absent after the spin-up. During the transient simulation (1700–2100), climate is simulated by adding an anomaly pattern, scaled by global mean temperature change relative to 1700, to the continuously recycled CRU climatology (temperature, precipitation, cloud cover). This implies that unforced variability is identical in all simulations. We focus on results after 1800 but chose an early start of the transient simulation (1700) in order to minimise effects of the initial equilibrium assumption for LUC-related fluxes. For the historical period and the future "business-as-usual" scenario (RCP8.5), we apply CMIP5 standard inputs (Taylor et al., 2012). Land use change is simulated following the Generated Transitions Method, including shifting cultivation-type agriculture and wood harvesting, as described in Stocker et al. (2014). In contrast to the previous studies by Stocker et al. (2013a) and Stocker et al. (2014), we apply the model at a coarser spatial resolution (2.5° × 3.75°, instead of 1° × 1°). This has negligible effects (see Sect. 5). LUC-related CO_2 emissions are calculated as the difference in the land-atmosphere CO_2 exchange flux between the simulation with and without LUC using Eq. (2) for the bookkeeping, Eq. (4) for the coupled, and Eq. (3) for the offline setup. In the coupled ESM setup, atmospheric CO_2 concentrations and climate evolve interactively in response to the respective forcings. In the offline model setup following the D3 method, we directly prescribe climate fields and CO_2 concentrations to the vegetation component (LPX model). In this case, climate and CO_2 are taken from the output of the coupled ESM simulation, driven by FF and LUC ($F_{\text{LUC}}^{\text{FF+LUC}}$) and are prescribed to both offline simulations, with and without LUC. This corresponds conceptually to the common setup chosen for D3-type simulations, but instead of prescribing CO_2 and climate from observations (which is the result of FF and LUC as well), we prescribe it from the coupled model output here in order to exclude differences in forcings between the coupled (E2) and offline (D3) setups, and to focus on differences in computed emissions implied by the different definitions.

The model is run in a set of simulations (see Table 1) that allows us to disentangle flux components eRSS and eLFB and to assess the additivity assumption ($\Delta f^{\text{FF+LUC}} = \Delta f^{\text{FF}} + \Delta f^{\text{LUC}} + \delta$). Using the description of decomposed fluxes given in Table 2 and the definition of eRSS in Eq. (7), the replaced sinks/sources flux component can be derived from simulations described in Table 1 as

$$e\text{RSS} = F_{\text{LUC}}^{\text{FF+LUC}} - F_{\text{LUC}}^{\text{LUC}} - F_{0}^{\text{FF}} + (A_0 - \Delta A)\,\delta_{\text{und}} + \Delta A \delta_{\text{dis}}. \quad (15)$$

Again, we may ignore the synergy terms δ. The expression of Eq. (15) also follows intuition. It represents the flux induced by environmental conditions caused by fossil fuel emissions in a world with LUC ($F_{\text{LUC}}^{\text{FF+LUC}} - F_{\text{LUC}}^{\text{LUC}}$) and a world without LUC ($F_{0}^{\text{FF}} - F_{0}^{0}$). The last term is zero, except for un-

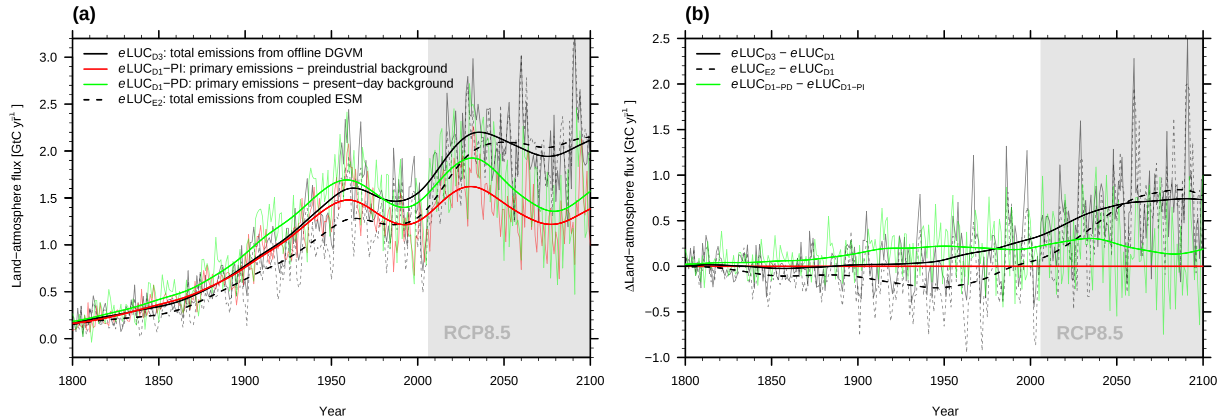

Figure 2. (a) Annual land use change emissions as quantified following different methods. **(b)** Difference of different *e*LUC definitions relative to *e*LUCdI, quantified under preindustrial boundary conditions. Total emissions derived from an offline, concentration-driven DGVM setup (D3 method) are given by black solid lines. Total emissions derived from a coupled, emission-driven ESM setup (E2 method) are given by black dashed lines. Primary emissions are given by coloured lines under constant pre-industrial (red) and constant present-day (green) environmental conditions (climate, CO_2, N deposition). Time series are calculated following Eqs. (2)–(4), where F is the global total land-atmosphere CO_2 flux in the respective simulation. Bold lines are splines of annual emissions given by thin lines. Results are from simulations following CMIP5 model inputs (historical until 2005, RCP8.5 until 2099).

Table 2. Flux decomposition for model setups described in Table 1. A_0 is land area at the reference state, ΔA is the area of land converted relative to the reference state. Δf_{und} and Δf_{dis} are the fluxes on unconverted and converted land induced by environmental change. The underlying driver of environmental change is given by the superscripts. f^0 is the flux due to direct impacts of land conversion, not including effects of environmental change. F_0^0 is zero except for the flux arising from unforced climate variability. The component flux $A_0\,\Delta f_{\text{und}}^{\text{LUC}}$ has not been named explicitly. Synergy terms are ignored in this table. Note that fluxes F generally refer to global totals for a given point in time t. Thus, for example $F_0^{\text{FF}}(t) = \int_{x,y} A_0(x,y)\,\Delta f_{\text{und}}^{\text{FF}}(x,y,t)\,\mathrm{d}x\,\mathrm{d}y$. For simplicity, we have dropped the time and space dimensions.

Setup	Decomposed flux	Component fluxes
$F_{\text{LUC}}^{\text{FF+LUC}}$	$(A_0-\Delta A)\,\Delta f_{\text{und}}^{\text{FF+LUC}} + \Delta A\, f^0 + \Delta A\,\Delta f_{\text{dis}}^{\text{FF+LUC}}$	$e\text{PS} + e\text{LUC}_0 + e\text{RSS} + e\text{LFB}$
$F_{\text{LUC}}^{\text{LUC}}$	$(A_0-\Delta A)\,\Delta f_{\text{und}}^{\text{LUC}} + \Delta A\, f^0 + \Delta A\,\Delta f_{\text{dis}}^{\text{LUC}}$	$e\text{LUC}_0 + e\text{LFB}$
F_0^{FF}	$A_0\,\Delta f_{\text{und}}^{\text{FF}}$	$e\text{PS}$
F_0^{LUC}	$A_0\,\Delta f_{\text{und}}^{\text{LUC}}$	$A_0\,\Delta f_{\text{und}}^{\text{LUC}}$
$F_0^{\text{FF+LUC}}$	$A_0\,\Delta f_{\text{und}}^{\text{FF+LUC}}$	$e\text{PS} + A_0\,\Delta f_{\text{und}}^{\text{LUC}}$
F_{LUC}^0	$\Delta A\, f^0$	$e\text{LUC}_0$
F_0^0	~ 0	~ 0

forced variability, as neither LUC nor changing environmental conditions are acting. Alternatively, *e*RSS can also be derived as $(F_{\text{LUC}}^{\text{FF+LUC}} - F_0^{\text{FF+LUC}}) - (F_{\text{LUC}}^{\text{LUC}} - F_0^{\text{LUC}})$, which is formally identical to Eq. (15), assuming additivity of the FF and LUC forcings. Analogously, the land use feedback flux can be derived as

$$e\text{LFB} = F_{\text{LUC}}^{\text{LUC}} - F_{\text{LUC}}^0. \quad (16)$$

Also this can be understood intuitively. *e*LFB represents the total land-atmosphere flux in a world with LUC (but without fossil fuel emissions), $F_{\text{LUC}}^{\text{LUC}}$, minus the direct effects of LUC, F_{LUC}^0. In other words, it represents the secondary flux caused by LUC alone. Again, alternatively *e*LFB can be derived as $F_{\text{LUC}}^{\text{FF+LUC}} - F_{\text{LUC}}^{\text{FF}}$, which is identical to Eq. (16), except for synergy effects.

5 Results

Figure 1 reveals that global fluxes due to FF and due to LUC forcing alone combine in an almost perfectly additive fashion to the flux induced by the combined effect of FF and LUC up to present and discernible deviations (δ) emerge only in a future scenario of continuously rising CO_2 and changing climate and contribute $\sim$ 10–20 % by 2100 in RCP8.5. This confirms the validity of the additivity assump-

Table 3. Cumulative emissions (GtC) over historical and future period for different methods ($e\mathrm{LUC_{D1}}$, $e\mathrm{LUC_{D3}}$, $e\mathrm{LUC_{E2}}$) and component fluxes (eRSS, eLFB). $e\mathrm{LUC_{D1}}$-PI and $e\mathrm{LUC_{D1}}$-PD refer are quantified under preindustrial (PI) and present-day (PD) environmental conditions.

	1850–2004	2005–2099
$e\mathrm{LUC_{D1}}$-PI	152	133
$e\mathrm{LUC_{D1}}$-PD	177	153
$e\mathrm{LUC_{D3}}$	164	192
$e\mathrm{LUC_{E2}}$	133	188
eRSS	9	71
eLFB	−26	−17

tion ($\Delta f^{\mathrm{FF+LUC}} = \Delta f^{\mathrm{FF}} + \Delta f^{\mathrm{LUC}} + \delta$) that underpins the flux component decomposition in Sect. 3.

Figure 2 illustrates annual emissions from LUC as quantified from the different approaches. During the historical period, the offline quantification (D3) suggests ∼ 23 % higher emissions than the coupled setup (E2). Cumulative emissions amount to 164 GtC with D3 and 133 GtC with E2 (AD 1850–2005, see Table 3). SM08 applied observational CO_2 and climate in simulations used for D3. They found slightly higher differences of D3 vs. E2 (30 % higher in their D3). Arora and Boer (2010) report a difference of ∼ 100 % for a case where they only used CO_2 concentrations from their interactive $F_{\mathrm{LUC}}^{\mathrm{FF+LUC}}$ to force their $F_{0}^{\mathrm{FF+LUC}}$ simulation. A stronger effect in this case appears plausible as the replaced sinks/sources flux due to climate and CO_2 effects are generally opposing (Strassmann et al., 2008). Stocker et al. (2014) applied the same model at a $1° \times 1°$ resolution following the D3 and D1 methods to quantify "total" and "primary" LUC emissions. Results at the finer resolution (165 GtC for "total GNT" in their Table 3) are virtually identical to the present estimate. The bookkeeping method yields cumulative historical fluxes of 152 and 177 GtC under preindustrial and present-day environmental conditions. Primary emissions under preindustrial and present-day background exhibit largely identical temporal trends but differ in absolute magnitude. 16 % higher emissions under present-day conditions are due to generally larger C density in natural (non-cropland and non-pasture) vegetation and soils simulated under elevated CO_2 (364 ppm) and the warmer climate (corresponding to years AD 1982–2012 in the CRU TS 3.21 data set (Mitchell and Jones, 2005)). Differences in constant environmental conditions thus have qualitatively the same effect as uncertainty in C stocks on natural and agricultural land. I.e. eLUCdI scales linearly with simulated differences in natural and agricultural land and the trends in eLUCdI derived under preindustrial and present-day environmental conditions are identical, but markedly different from trends in eLUCdIII and eLUCeII.

Cumulative historical emissions following the D1 method under preindustrial (present-day) conditions are 14 % (33 %) higher than suggested by the E2 method. These differences are substantial and are on the order of the model range as presented in intercomparison studies (Sitch et al., 2008; Le Quéré et al., 2015) or on the order of effects of accounting for wood harvest and shifting cultivation (Stocker et al., 2014). For the future period (AD 2006–2099) following RCP8.5, cumulative emissions (2004–2099) for the D3 and E2 method are on the same order (192 and 188 GtC), but considerably higher than for the D1 method (133 and 153 GtC under preindustrial and present-day conditions). Differences with respect to the relative increase from present-day emission levels (average over 1995–2004) to projected levels in the last decade of the 21st century are even larger. Following the D1 method, the increase is 22 % (34 %) when holding conditions constant at preindustrial (present-day) levels. Due to different inclusion of secondary fluxes, the projected increase following the D3 method is 67 and 121 % following E2.

Figure 3 illustrates the different flux components of total emissions from LUC following the E2 method and reveals the underpinnings of the discrepant levels and trends of emissions when quantified with different methods. During the historical period (AD 1850–2005), eRSS cumulatively adds 6 % to primary emissions, similar as in SM08 (5 %), while eLFB reduces them by 17 %, similar as in SM08 (18 %) but less than in Pongratz et al. (2009) and Stocker et al. (2011) (30–40 %). At present, eRSS and eLFB are of similar magni-

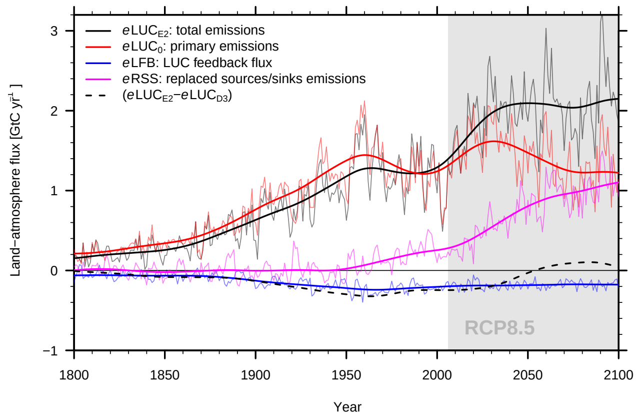

Figure 3. Flux components of land use change emissions. Total emissions as derived from an emission-driven, coupled ESM setup (E2 method), and calculated with Eq. (4), are given by the black lines. Primary emissions under preindustrial boundary conditions are given by red lines. These correspond to curves in Fig. 2. The replaced sinks/sources flux (eRSS) and the land use change feedback flux (eLFB) are given by magenta and blue lines, respectively. The difference between total emissions quantified by D3 method (see black solid line in Fig. 2) and E2 method is given by the black dashed line. Time series are calculated following Eqs. (2), (4), (15), and (16). Bold lines are splines of annual emissions given by thin lines. Results are from simulations following CMIP5 model inputs (historical until 2005, RCP8.5 until 2099).

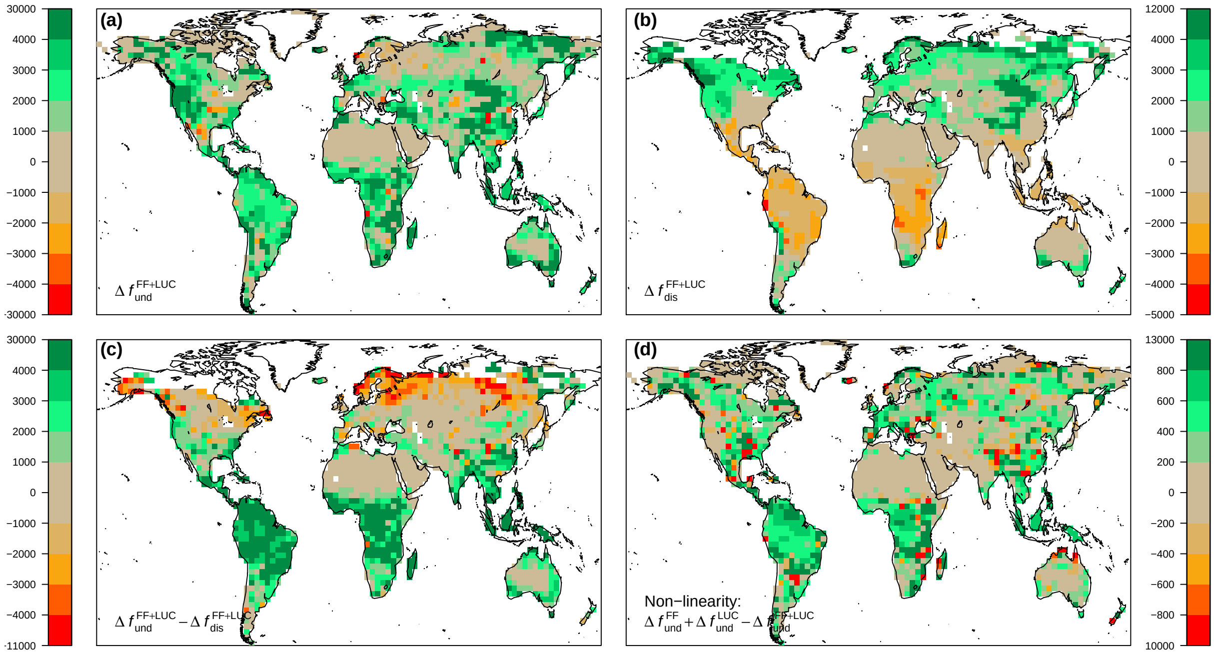

Figure 4. Top row panels: cumulative atmosphere-land C flux (kgC m^{-2}) induced by environmental change from 1700 to 2100 on undisturbed **(a)** and disturbed land (**b**; mean of cropland and pasture, weighted by respective area shares). Here, "disturbed" is approximated by cropland and pasture area (small at 1700), and "undisturbed" by natural area. The period 2005–2100 follows the RCP8.5 scenario. Climate and CO_2 are prescribed from the outputs of the coupled simulation (offline simulation $F_0^{\mathrm{FF+LUC}}$ uses outputs from $F_{\mathrm{LUC}}^{\mathrm{FF+LUC}}$). **(c)** Difference of flux occurring on undisturbed and disturbed land $f_{\mathrm{und}}^{\mathrm{FF+LUC}} - f_{\mathrm{dis}}^{\mathrm{FF+LUC}}$. **(d)** Spatial distribution of synergy effects, cumulative in year 2100. Its global total over time is expressed also in Fig. 1 (difference between black and red curves).

tude, hence total (eLUCeII) and primary emissions (eLUCo) are at approximately the same level. In RCP8.5, atmospheric CO_2 and temperatures continue to grow, while land conversion rates and primary emissions are stabilised. As a result eLFB is stabilised, while eRSS continues to increase and contributes $\sim$50 % to total emissions in 2100. This explains the different trends in "total" (based on E2 and D3) versus primary emissions.

The difference between eLUCeII and eLUCdIII is of approximately the same magnitude as eLFB , although slightly smaller, and exhibits a trend that is closely matched by eLFB until roughly AD 2030 (see dashed line in Fig. 3). This is expected as the difference, derived in Eq. (13), is equal to $A_0(\Delta f_{\mathrm{und}}^{\mathrm{LUC}} + \delta_{\mathrm{und}})$, and thus resembles the definition of eLFB (see Eq. 8).

Secondary emissions are determined by the magnitude of C sinks and sources induced by environmental change, occurring differently on disturbed (agricultural) and undisturbed (natural) land. Figure 4 reveals that the C sink capacity on natural land under rising CO_2 and a changing climate (year 2100, RCP8.5) is greatest in semi-arid regions of the Tropics and Subtropics and along the boreal treeline. In contrast, agricultural land at low latitudes acts as a net C source under environmental change and a net sink at high latitudes. The difference between the sink strength on natural and agricultural land is related to the eRSS component flux and reveals that the Tropics are the most efficient potential C sinks. Interestingly, at high latitudes, agricultural vegetation is an even more efficient C sink than natural vegetation. Figure 4 also provides information about the spatial distribution of synergy effects from the combination of the FF and LUC forcings, corresponding to the differences between the red and the black curves in Fig. 1 in year 2100. The sum of individual effects is greater than their combination in almost all vegetated areas, but most pronounced along the transition zone between forest and open woodland. Opposite effects are simulated in individual gridcells and are likely related to the threshold-behaviour of the dominant vegetation type.

6 Discussion

To quantify the differences in eLUC quantifications by coupled ESM (E2 method), offline DGVMs (D3 method), and the bookkeeping method (D1 method), we applied a model setup where differences stemming from driving data are removed. Then, discrepancies in total eLUC arise exclusively from the applied methods (D1, D3, E2). Our results suggest that such discrepancies in global eLUC estimates are substantial for the historical period and imply strikingly different trends in eLUC for a future business-as-usual scenario.

These differences stem from the implicit inclusion of secondary flux components. As we have pointed out, secondary fluxes derived from offline vegetation model setups are conceptually not identical to what is commonly referred to as the replaced sinks/sources flux or the land use feedback, nor the sum of the two.

Land use change is a substantial driver of the observed CO_2 increase and has contributed about 25 % to total anthropogenic CO_2 emissions for the period 1870–2014 (Le Quéré et al., 2015). Current (2004–2013) emission levels are $0.9 \pm 0.5\,\mathrm{GtC\,yr^{-1}}$ (Le Quéré et al., 2015). Reducing emissions from deforestation and forest degradation is now an important part of international climate change mitigation efforts under the United Nation Framework Convention on Climate Change. Periodically issued synthesis reports by the IPCC (Ciais et al., 2013), annually updated CO_2 flux quantifications by the Global Carbon Project (Le Quéré et al., 2015), as well as multi-model intercomparison projects (CMIP5, 2009; CMIP6, 2014; TRENDY, 2015) provide valuable information on LUC CO_2 emissions. However, values derived from different approaches are commonly presented alongside and respective uncertainty ranges partly stem from implicit methodological differences. The lack of a standard methodological protocol for LUC emission estimates and the inclusion of secondary fluxes also obscures the scientific interpretation of model results and their comparison with observational data. Below, we outline two different perspectives on what "emissions from LUC" may represent.

6.1 Carbon budget accounting

On local to regional scales, the land C budget on natural (or weakly managed) land is derived from forest inventory data (Pan et al., 2011), net ecosystem exchange estimates from eddy flux towers (Valentini et al., 2000; Friend et al., 2007), growth assessments from tree ring data, satellite data (Baccini et al., 2012; Harris et al., 2012), and atmospheric inversions of the CO_2 distribution using transport models (Gatti et al., 2014). As pointed out also by Houghton (2013) and PG14, it is in general not possible to disentangle to which extent such observation-based estimates of the local net air-land C flux are driven by environmental change induced by fossil fuel combustion or by remote LUC. Fossil fuel emission estimates do not, by definition, include any such secondary effects. *e*LUC estimates including the *e*LFB component are thus conceptually inconsistent with reported values for fossil fuel emissions. Similarly, comparing *e*LUC quantifications that include *e*RSS with up-scaled local-to-regional scale observation-based information is confounded by this virtual, because not realised, flux component.

This is relevant for continental-to-global scale C budget accounting, where CO_2 exchange fluxes between the major reservoirs (ocean, atmosphere, land, fossil fuel reserves) and the airborne fraction of anthropogenic CO_2 emissions are quantified (Canadell et al., 2007; Le Quere et al., 2009; Knorr, 2009; Ballantyne et al., 2012; Le Quéré et al., 2015). By definition, estimates for *e*LUC directly translate into the magnitude of the implied residual terrestrial C sink (see Fig. 5) and the airborne fraction. Inclusion of secondary LUC fluxes thus determines where the system boundaries between *e*LUC and the residual terrestrial sink are drawn. The D3 method ascribes replaced sinks/sources (*e*RSS) to *e*LUC. This implies that the residual terrestrial sink represents a flux occurring in a hypothetical state before land conversion. This may be misleading in view of the actual reduction of land C sinks due to the reduction of natural vegetation. This reduction of the residual sink due to the replacement of natural by agricultural vegetation is only captured when basing its quantification on D1-type *e*LUC estimates.

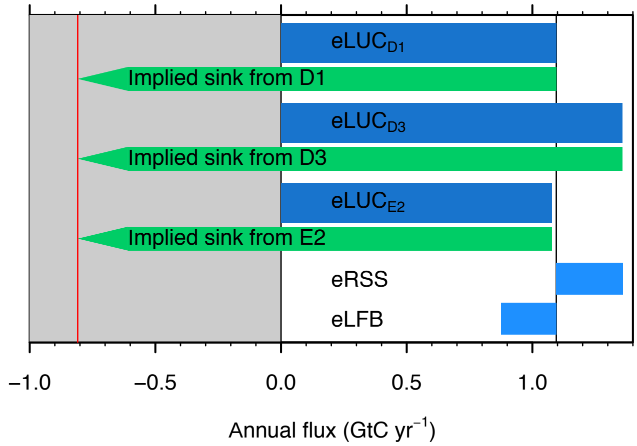

Figure 5. Land use change emissions (*e*LUC, dark blue bars) calculated from different methodologies and their implied residual terrestrial C sink (annual flux in $\mathrm{GtC\,yr^{-1}}$, mean over 1996–2005). The total terrestrial C balance is constrained by atmospheric measurements and is $-0.8\,\mathrm{GtC\,yr^{-1}}$ (mean over 1996–2005, (Le Quéré et al., 2014), left vertical line). It is independent of *e*LUC estimates. The residual terrestrial C sink (green arrow) is defined as the difference of *e*LUC and the total terrestrial C balance. Depending on the definition of *e*LUC, the residual C sink is affected by inclusion of secondary fluxes (light blue bars, *e*RSS and *e*LFB) into *e*LUC.

Processes determining primary emissions are directly observable (i.e. C stocks in vegetation and soils, C loss during deforestation, fate of product pools, soil C evolution after conversion). Such information may be used to benchmark simulated *e*LUCdI. As discussed by Houghton (2013), separating environmental effects from management effects (direct effects from LUC) also serves to lower uncertainty in *e*LUC estimates as it excludes effects of CO_2 fertilisation and climate impacts on C stocks – processes less well understood and notoriously challenging to simulate. These uncertainties explain the relatively large differences in quantifications of *e*LFB as indicated in Sect. 5. Houghton (2013) argued that this type of uncertainty should be solely ascribed to the residual budget term to reflect which terms are subject to the largest uncertainties.

Our results also demonstrated the differences in *e*LUCdI implied by prescribing preindustrial versus present-day environmental conditions (see Fig. 2). It may be argued that prescribing present-day conditions allows best comparability with bookkeeping estimates where observational data of C density in natural and agricultural land are used, that inherently represents conditions of the recent past. However, we note that total terrestrial C storage is 1775, 1838, and 1982 GtC in our simulations for $F_{\mathrm{LUC}}^{0-\mathrm{PI}}$, $F_{\mathrm{LUC}}^{\mathrm{FF+LUC}}$, and $F_{\mathrm{LUC}}^{0-\mathrm{PD}}$ (mean over years 2000–2004; superscript "$0-\mathrm{PI}$" ["$0-\mathrm{PD}$"] refers to constant preindustrial [present-day] environmental conditions). I.e. the case where C stocks are responding to transient changes in CO_2 and climate ($F_{\mathrm{LUC}}^{\mathrm{FF+LUC}}$ – the closest analogue to what observational data represent) is farther from its equilibrium to be attained under present-day conditions than its equilibrium under preindustrial conditions. In other words, quantifying *e*LUCdI under preindustrial conditions is a viable and pragmatic solution.

Adopting the D1 method for benchmarking, model-intercomparison studies and syntheses based on multiple methods has the critical practical advantage of being the "least common denominator" that can be followed using empirically based bookkeeping methods, offline vegetation models, as well as Earth System Models. Quantification of *e*LUCdI simply requires a preindustrial control simulation (no forcings, constant environmental conditions) which is already part of the CMIP6 DECK simulations (CMIP6, 2014), and one additional run with transient LUC while environmental conditions are held constant at preindustrial levels (see Sect. 4). This could be achieved by Earth System Models without computationally demanding coupled model setups involving interactive atmosphere and ocean, but using prescribed preindustrial climate and CO_2 and their land models in a stand-alone mode instead. Serving as an "entry card" for future model intercomparisons, this would guarantee continuity and comparability between model development cycles and periodically repeated syntheses.

6.2 LUC in the Earth system

LUC effects on climate and the Earth system are not fully captured by their direct (primary) CO_2 emissions. Vegetation cover change also affects the local surface energy and water balances (biogeophysical effects) and emissions of other greenhouse gases. Deforestation by purposely set fires is associated with emissions of a range of radiatively active compounds (e.g. CH_4, CO, NO_x), wetland management may have strong effects on CH_4 emissions, and the application of mineral fertiliser and manure on agricultural land increases soil N_2O emissions and sets in motion a cascade of detrimental environmental effects (Galloway et al., 2003), many of which directly or indirectly affect climate (Erisman et al., 2011).

Apart from these direct effects where LUC can be regarded as a forcing acting upon the Earth system, LUC also modifies the land response to external forcings. E.g. the replacement of woody vegetation with crops reduces the CO_2 -driven fertilisation sink. Thus, LUC affects the strength of the land-climate feedback (Stocker et al., 2013a). Furthermore, primary LUC emissions induce a secondary C uptake flux as a feedback to elevated CO_2 concentrations caused by primary emissions. These feedback effects are captured by the LUC flux components *e*RSS and *e*LFB. Coupled Earth System Models featuring an active C cycle require a preindustrial control simulation and a fossil C emission-driven simulation over the industrial period where transient LUC and other climate and environmental forcings are activated to quantify the sum of primary and secondary land use C emissions (method E2). Such an emission-driven, land use-enabled simulation may become part of the CMIP6 protocol. Additional simulations are required to quantify individual components separately (see Table 2).

The results presented here demonstrate the importance of secondary fluxes under slowing land conversion rates and continuously increasing CO_2. In RCP8.5, *e*RSS is set to increase to $\pm 1\,\mathrm{GtC\,yr^{-1}}$ and make up around half of *e*LUCeII by the end of the 21st century. Hence, in order to capture the overall effect of LUC on the terrestrial C cycle feedback, these must be accounted for. However, we recommend to account for the effect of secondary LUC-related fluxes in global C budget assessments as an anthropogenic modification of the terrestrial C sink. We emphasize that offline vegetation model setups are not capable of separating *e*RSS and *e*LFB as defined here.

7 Conclusions

Estimates of CO_2 emissions from land use are essential to quantify the global C budget and inform climate change mitigation policy. However, inconsistent methodologies have been applied in syntheses based on multiple models and methods. In order to guarantee comparability and continuity, we recommend that modelling studies provide estimates derived under constant, preindustrial boundary conditions (D1 method). This method can be followed by offline vegetation models and Earth System Models, and is best comparable to observation-based estimates following the bookkeeping approach. This implies that the residual terrestrial sink derived from the global C budget includes the sink flux stimulated by environmental changes in response to LUC and reflects effects of replacement of potential C sinks due to land conversion. We have suggested how coupled, emission-driven Earth System Models may be applied to separate component fluxes defined here. Such analyses are essential to capture the full impact of LUC on climate and CO_2.

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